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Materials modelling for selective heating and press hardening of boron steel panels with graded microstructures

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Abstract

In order to model a novel and complete hot stamping process for forming boron steel panels with graded microstructures, three sets of physically-based material models have been introduced. They are an austenite transformation model for boron steel under selective heating, a viscoplastic-damage constitutive model and a martensite and bainite transformation model for boron steel under press hardening conditions. Material constants are given, determined from the results of fundamental experiments. In addition, the determined unified constitutive equations have been embedded in the commercial Finite Element code LS-DYNA via user defined subroutines, where the three sets of models are integrated through internal state variables. An FE process simulation model and numerical procedure have been established and are illustrated.

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Nomenclature

| | |
|---|--|
| \dot{N} | austenite nucleation rate |
| \dot{v} , \dot{V}_e | volume growth rate of an austenite nucleus, extended volume growth rate of austenite phase |
| $f_{\#}$, f_{As} | volume fraction of a phase, saturated volume fraction of austenite |
| $\#_{A,P,F,B,M,(P+F)}$ | variable of austenite, pearlite, ferrite, bainite, martensite, and initial phase |
| $\bar{\rho}$ | normalised dislocation density |
| ω | damage |
| H | isotropic strain hardening, MPa |
| k | initial yield stress, MPa |
| h | hardness, HV |
| $\varepsilon^T, \varepsilon^P, \varepsilon^E$ | total (true) strain, plastic (true) strain, elastic (true) strain |
| σ | true stress/flow stress, MPa |
| r^* , \dot{r} | critical radius and growth rate of bainite particles |
| $Q_{\#}$ | activation energy |

1. Introduction

Hot stamping of boron steel components with tailored properties has drawn great attention in recent years, as it introduces the potential for making components that conform more fully to functional requirements (Maikranz-Valentin et al., 2008). Extensive studies have been carried out to tune microstructural distribution by selectively cooling the part (Guiles et al., 2008; Thomas et al., 2009). However, because a long cooling time is required to obtain ductile phases, there is an intrinsic conflict with the industrial requirement for short cycle times. This was pointed out by Li et al. (2012); at the same time, another process strategy, named Selective Heating and Press Hardening (SHPH), was proposed and validated by the same group to overcome the shortcoming. It allows optimization of the structural performance of a press hardened part by means of austenite transformation control through different heat treatment of a blank, prior to forming. Thus no extra cooling time is required.

To implement the strategy properly, materials modelling of the phase transformation and thermo-mechanical behaviour of boron steel under SHPH conditions are necessary. However, austenite formation in boron steel, as a key aspect of this new strategy, has not drawn much attention, compared with its decomposition (Azizi-Alizamini et al., 2010). It is found that the transformations of austenite under isothermal (Gaude-Fugarolas et al., 2003; Asadi Asadabad et al., 2008) and non-isothermal conditions (Martín et al., 2006; Cai et al., 2011) have been always modelled separately. Thus the effects of heating rate on the subsequent isothermal transformation, in a real hot stamping situation, cannot yet be accounted for. In addition, deformation in this strategy involves boron steel in various phase states rather than only austenite, as in the conventional process, yet no published work on the thermomechanical properties of boron steel in ferritic/pearlitic state under hot stamping conditions has been found. The aim of this study is to develop comprehensive material models and establish integrated process simulation for the forming process.

2. Devolvement of unified constitutive equations

2.1. Austenite transformation model for boron steel during selective heating

An austenite transformation model, based on the mechanisms of nucleation, growth and impingement, was developed to describe the formation of austenite in boron steel under selective heating conditions. The innovation of the model is its capability to describe both partial austenitization in boron steel under intercritical annealing, and full austenitization under both continuous heating and steady soaking. This is essential to enable the precise modeling of the SHPH process. To describe the features and interactive effects of physical phenomena during the transformation, the unified theory is used in this study, for the development of the austenite formation model consisting of multiple evolutionary equations as below:

$$\dot{N} = (A_0 + A_1 \dot{T}^{\varphi_A}) \exp(-Q_N/RT), \quad \text{if } f_A > f_P, \dot{N} = 0 \quad (1)$$

$$\dot{v} = (B_0 + B_1 \dot{T}^{\varphi_B}) \exp(-Q_v/RT), \quad (2)$$

$$\dot{V}_e = N\dot{v}, \quad (3)$$

$$\dot{f}_A = (f_{As}^m - f_A^m) \dot{V}_e / (1 + V_e)^n, \quad (4)$$

$$\text{where } f_{As} = (C_2/\pi) \arctan(C(T/T_{As} - 1)) + C_3, \quad (5)$$

is the saturated volume fraction of austenite, and, the parameters m and n are defined as:

$$\begin{aligned} m &= 1 & (f_A \leq f_P) \\ &= 1 - m_0(f_A - f_P) & (f_A > f_P), \end{aligned} \quad n = n_0 \dot{f}_A^{\varphi_n} \quad (6, 7)$$

where \dot{N} and N are the nucleation rate and nuclei quantity of austenite per unit sample volume, respectively; \dot{v} is the volume growth rate of an austenite nucleus; V_e is the extend volume of transformed austenite per unit sample volume, and its growth rate is modelled using Eq. (3); f_A is the volume fraction of austenite and its formation rate is expressed by Eq. (4); f_{As} is the saturated volume fraction of austenite which is a function of temperature in Eq. (5); m and n are parameters to characterise the impingement mechanism; R is the gas constant and T is the absolute temperature; f_P is the volume fraction of pearlite in the initial structure; $A_0, A_1, \varphi_A, Q_N, B_0, B_1, \varphi_B, Q_v, C_1, C_2, C_3, T_m, m_0, n_0, \varphi_n$ are constants to be determined from experimental data.

The materials model is a set of Ordinary Differential Equations (ODE) in terms of time t , which can be solved with given initial values for the variables. In the numerical integration of solving the equations, at $t = 0$, $N = 0$, $v = 0$, $V_e = 0$, and $f_A = 2\%$ for the starting temperature of $A_{e1} = 993$ K, which was defined according to information provided by the material supplier. The model was calibrated by fitting the computed volume fraction of austenite to experimental results by adjusting the values of constants within the equations. The trial and error method was adopted in the study. Fig. 1(a) shows the testing programme of heat treatments with different heating conditions. Fig. 1(b) and (c) show the comparison of experimental (symbols) and computed (solid curves) volume fraction of austenite formation with time under different heating rates and soaking temperatures. Good agreements have been obtained and the features of experimental data are exhibited clearly from the computed curves. The calibrated constants are listed in Table 1.

Table 1. Material constants for the austenite transformation equations (1) – (7).

| Q_N (J/mol) | Q_v (J/mol) | A_0 | A_1 | B_0 | B_1 | φ_A | φ_B | A_{e1} (K) |
|---------------|---------------|--------|--------------|-------|-------|-------------|-------------|---------------|
| 149000 | 40000 | 176000 | 2.2e5 | 9.2 | 9.2 | 1.4 | 0.12 | 993 |
| C_1 | C_2 | C_3 | T_{As} (K) | m_0 | f_P | n_0 | φ_n | R (J/mol·K) |
| 36.0 | 1.2 | 0.475 | 1037 | 1.05 | 0.22 | 2.1 | 0.155 | 8.314 |

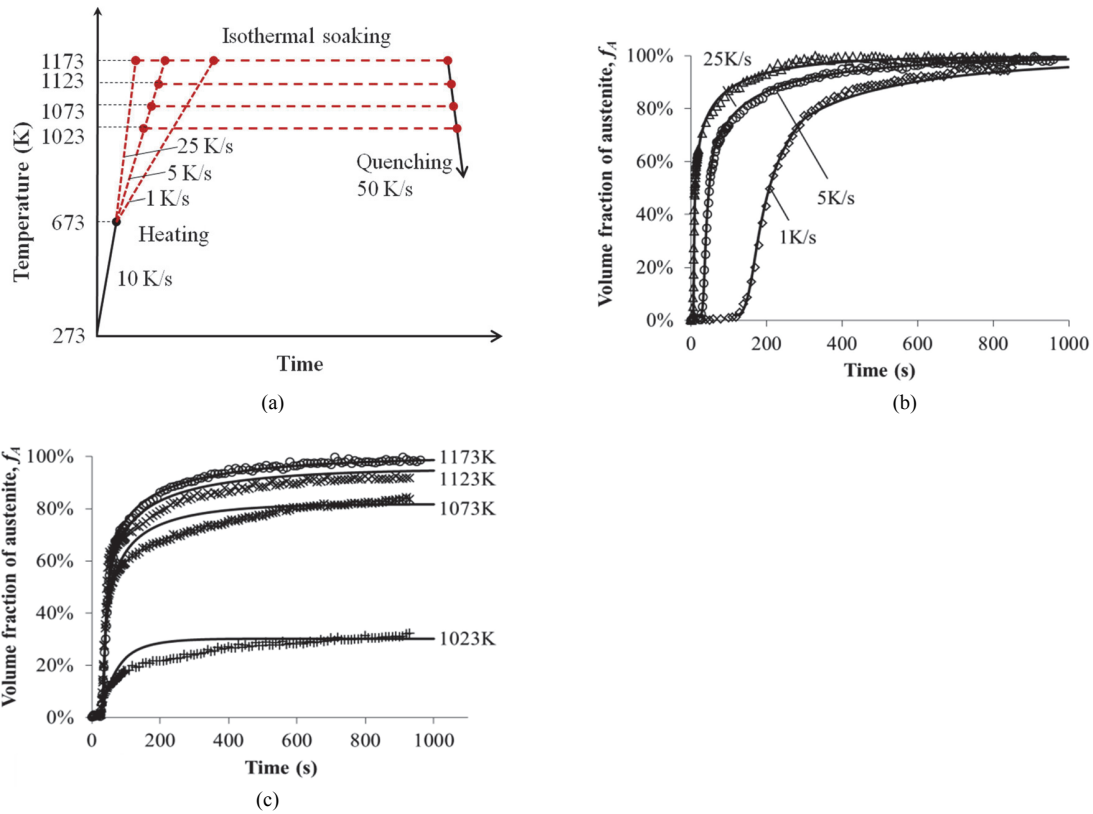


Fig. 1. (a) Testing programme with different heating rates and soaking temperatures, and comparison of experimental (symbols) and computed (solid curves) volume fractions of austenite formation under (b) different heating rates (soaking temperature: 1173K) and (c) different soaking temperatures (heating rate: 5K/s).

2.2. Unified viscoplastic-damage constitutive equations for boron steel under hot stamping conditions

A viscoplastic-damage constitutive model developed by Lin et al. (2011), which takes the mechanisms of dislocation-driven evolution processes such as hardening, dynamic and static recovery and damage into account, were adopted to describe the deformation behaviour of boron steel under hot stamping conditions:

$$\dot{\varepsilon}^P = \dot{\varepsilon}^o \left(\left(\left| \frac{\sigma}{1-\omega} \right| - k - H \right) / K \right)^{n_v} / (1-\omega)^{\gamma_1}, \text{ if } \left| \frac{\sigma}{1-\omega} \right| - k - H \leq 0, \quad \dot{\varepsilon}^P = 0, \quad (8)$$

$$\dot{\rho} = A(1-\bar{\rho}) \left| \dot{\varepsilon}^P \right| - C\bar{\rho}^{\gamma_2}, \quad (9)$$

$$H = B\bar{\rho}^{n_R}, \quad (10)$$

$$\dot{\omega} = \beta \sigma^{\gamma_3} \left| \dot{\varepsilon}^P \right| / (1-\omega)^{\varphi}, \quad (11)$$

$$\sigma = E(1-\omega) \left(\varepsilon^T - \varepsilon^P \right), \quad (12)$$

where the temperature dependent parameters are defined by:

$$k = k_0 \exp(Q/RT), \quad K = K_0 \exp(Q/RT), \quad n_v = n_{v0} \exp(Q_n/RT), \quad B = B_0 \exp(Q_B/RT), \quad (13-19)$$

$$C = C_0 \exp(-Q_C/RT), \quad \beta = \beta_0 \exp(Q_\beta/RT), \quad E = E_0 \exp(Q_E/RT),$$

where R is the gas constant and T is the absolute temperature.

Eq. (8) is the flow law, representing that plastic strain rate $\dot{\varepsilon}^P$ is a function of flow stress σ , initial elastic limit k , and isotropic hardening H , with damage ω taken into account, where the term $1/(1-\omega)^{\gamma_1}$ is adopted to provide the equation with higher flexibility. If $\sigma > 0$, $\dot{\varepsilon}^o = 1$, and if $\sigma < 0$, $\dot{\varepsilon}^o = -1$. Eq. (9) is the dislocation density evolution law, which involves dislocation accumulation, and dynamic and static recovery. Eq. (10) is the isotropic hardening law formulated as a function of normalised dislocation density $\bar{\rho}$ given by Eq. (9). Eq. (11) is the evolution law of plasticity-induced damage ω . Eq. (12) is a modified Hooke's law, where E is Young's modulus of elasticity. Q , Q_n , Q_C , Q_B , Q_E , Q_β , k_0 , A , B_0 , C_0 , β_0 , K_0 , n_{f0} , φ , γ_1 , γ_2 , and γ_3 are constants to be determined from experimental data.

For both the austenite and initial phase of boron steel, hot tensile tests were conducted under different temperatures and strain rates. By fitting the true stress-strain curves, two sets of constants have been determined for the two phase states of boron steel, given in table 2.

Table 2. Material constants for viscoplastic-damage constitutive Eqs. (8) – (19).

| | Q (J/mol) | Q_n (J/mol) | Q_C (J/mol) | Q_B (J/mol) | Q_E (J/mol) | Q_β (J/mol) | k_0 (MPa) |
|---------------|-------------|---------------|---------------|---------------|---------------|---------------------------------|-------------|
| Austenite | 4000 | 50000 | 10000 | 24000 | 1400 | 8000 | 12.921 |
| Initial phase | 14800 | 1000 | 5000 | 27000 | 1400 | 7000 | 5.820 |
| | A | B_0 (MPa) | C_0 | E_0 (MPa) | K_0 (MPa) | R (J/mol·K) | φ |
| Austenite | 16 | 12.084 | 0.560 | 143800 | 31.354 | 8.314 | 10.5 |
| Initial phase | 0.248 | 12.224 | 0.213 | 150000 | 24.410 | 8.314 | 13.8 |
| | n_{f0} | n_R | γ_1 | γ_2 | γ_3 | β_0 (MPa $^{-\gamma_3}$) | |
| Austenite | 0.0185 | 0.4 | 3.4 | 1.55 | 0.5 | 5.996e-3 | |
| Initial phase | 4.33 | 0.4 | 3.1 | 1.54 | 0 | 0.052 | |

2.3. Phase transformation model for hot stamped boron steel during quenching

Since full press hardening is applied in the studied hot stamping process, martensite and bainite transformation during austenite decomposition are the main interests. A set of mechanism-based phase transformation models developed by Cai et al. (2011), to predict the evolution of bainite transformation during quenching, was adopted in this study to obtain the final volume fraction of martensite:

$$r^* = A_1 T_{eq} \left/ \left(T Q_V \sqrt{T_{eq} - T} + T T_{eq} \alpha_B \rho / \sqrt{T_{eq} - T} \right) \right. \quad (20)$$

$$\dot{r} = A_2 \exp \left(-|T - T_1|^{n_1} / B_1 \right) \quad (\text{when } T < T_{eq}), \quad (21)$$

$$\dot{f}_B = A_3 \dot{r} \left((r - r^*) / r \right)^{n_2} \exp \left(-(|T - T_2| / B_2)^{n_3} \right) (1 - f_B)^{n_4} \quad (\text{when } r > r^*). \quad (22)$$

Equation (20) is the formulation of a critical radius of bainite particles associated with a maximum excess free energy. The effect of deformation on the transformation is accounted via the normalised dislocation density which can be calculated through the equation (9). The growth rate of bainite phase particles is temperature dependent and follows the Gaussian-type function (21). The bainite transformation rate is expressed by equation (22). A_1 , A_2 , A_3 , B_1 , B_2 , n_1 , n_2 , n_3 , n_4 , T_1 , T_2 , Q_V , and α_B are constants and the determined values are presented in Table 3. After quenching, the final volume fraction of martensite can be obtained by: $f_M = 1 - f_B$.

Table 3. Material constants for the martensite and bainite transformation equations (20) – (22).

| T_1 (K) | n_1 | B_1 | A_2 | A_1 | Q_V (J/mol) | T_{eq} |
|------------|-------|---------|--------|---------|---------------|-----------|
| 980.0 | 3.542 | 7.408e7 | 0.7057 | 6.893e6 | 210550.0 | 983.0 |
| α_B | A_3 | B_2 | n_2 | n_3 | n_4 | T_2 (K) |
| 1290.0 | 0.27 | 80.396 | 0.009 | 80.551 | 1.45 | 813 |

3. Integrated process simulation

The developed material models allow prediction of the final properties of an as-formed part after selective heating and press hardening. Integrated process simulation for forming a boron steel beam with tailored properties was carried out by using finite element (FE) commercial software, LS-DYNA, with implementation of the material models via user defined subroutines. A set of multi-stage three-dimensional FE models are presented in Fig. 2. Quarter symmetric models were used for computation efficiency. Boundary conditions for each stage are given in

the figure. Shell elements were used for the blank, solid rigid elements were used for the heating blocks and dies. The blank (160mm half length) was selectively heated up by heating blocks (50mm half length) for 300s; afterwards, the blank with graded temperature distribution was formed, and quenched by cold dies (323K) for 20s. The flow chart in Fig. 2 illustrates the integration of material models for process simulation. Under given thermal conditions, the austenite distribution in a boron steel blank prior to forming can be predicted by simulating the selective heating process using the austenite formation model. Subsequently, the blank, incorporating austenite volume fraction f_A and temperature T data, was subjected to hot stamping in the thermo-mechanical simulation, where the deformation behaviour of the blank was described using the viscoplastic-damage model of boron steel. In this process, multiple phases of boron steel were subjected to hot deformation. Both the constitutive deformation behaviour of austenite and untransformed initial phase have been modelled and it is reasonable to calculate the flow stress response and state variables ($\bar{\rho}$, ω) in a transition zone using linear interpolation by knowing the f_A . In addition, the martensite and bainite transformation model was used to predict austenite decomposition during press hardening. The final volume fraction of martensite f_M at each element depends on not only the temperature profile but also the austenite volume fraction f_A and dislocation density $\bar{\rho}_A$ calculated through previous models. The hardness h of press hardened boron steel, as a function of f_M (see figure) proposed by Li et al. (2012), can also be calculated.

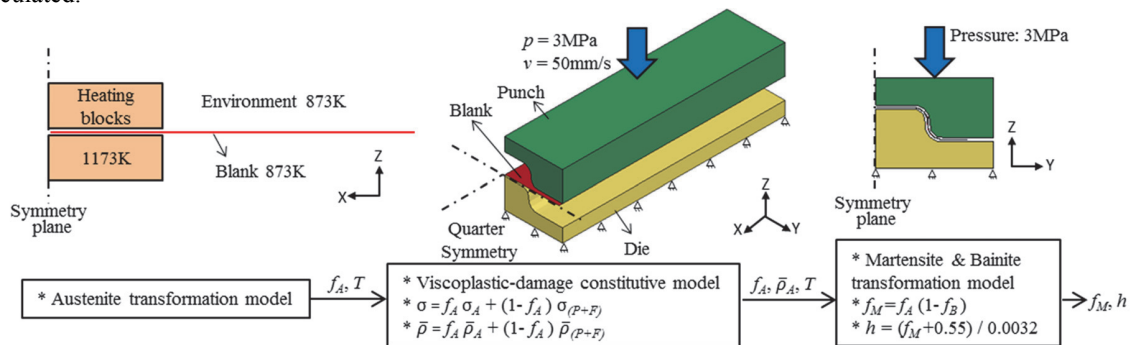


Fig. 2. FE models for selective heating and precess hardening of boron steel beam and flow chart for integration of material models.

Fig. 3 shows the graded austenite distribution in the boron steel blank after selective heating. The blank can be divided into a full austenite zone, a multiphase transition zone, and an untransformed initial phase zone. The history of temperature and evolution of austenite volume fraction at different locations are plotted. Location 'A' at the heating area shows the highest austenite transformation rate and final transformed value. Fig. 4 (a) shows the distribution of normalised dislocation density in the as-formed part. Along x-direction, higher $\bar{\rho}$ is shown at the initial phase zone, where the temperature is lower. Fig. 4 (b) shows the hardness distribution of the press hardened beam. The highest hardness is due to the highest martensite volume fraction occurrence, corresponding to the previous austenite zone.

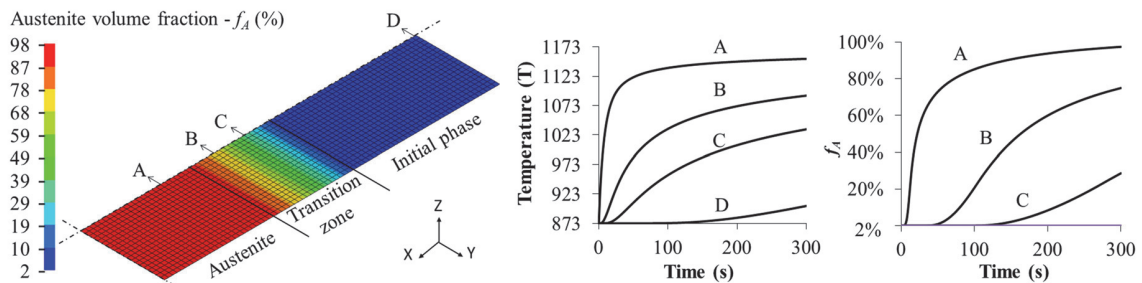


Fig. 3. Austenite distribution in the blank after selective heating; temperature profiles and evolution curves of f_A for different locations.

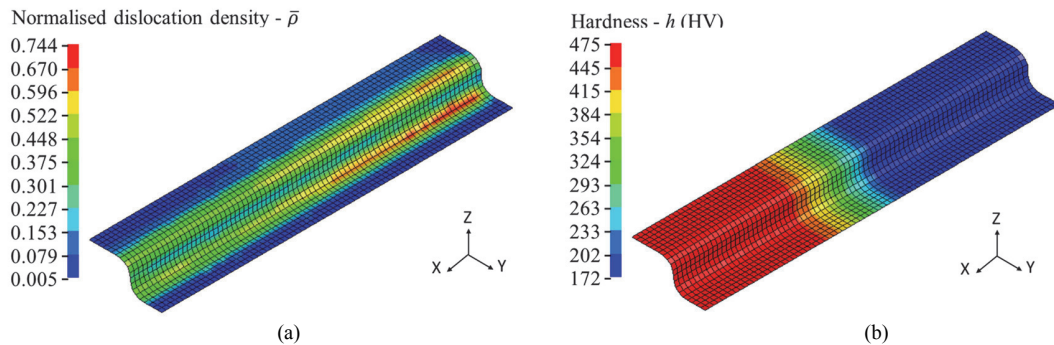


Fig. 4. (a) Normalised dislocation density distribution in the beam right after hot stamping; (b) hardness distribution in the press hardened beam.

4. Conclusions

An austenite transformation model has been developed to describe the austenitization of boron steel under complicated thermal conditions. A set of viscoplastic-damage constitutive equations have been extended to model the deformation of boron steel in multiple phase states. Process simulation of selective heating and press hardening of boron steel has been successfully established through the integration of the austenite transformation model, the viscoplastic-damage constitutive model, and a martensite and bainite phase transformation model. It has been demonstrated by achieving a boron steel panel beam with graded microstructures and mechanical properties. This study facilitates effective process control for the manufacture of graded press hardened steel products through materials modelling.

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